SIMULATIONS ON OPERATION OF THE FLASH INJECTOR IN LOW CHARGE REGIME

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Abstract

The overall bunch compression in FLASH is limited on the one hand by the rf tolerances and on the other hand by linearization of the particle distribution in the longitudinal phase space. While the last one has been significantly improved after the installation of the third harmonic system during the upgrade 2009-2010 [1], the constraint given by rf tolerances cannot be mitigated significantly. To avoid this limitation one has to operate with shorter bunches already at the injector. Since the bunch length is dominated there by the longitudinal space charge one has to go to lower bunch charges. Working points for the operation of the FLASH injector with 20-500pC bunches have been found by means of the optimization procedure based on the ASTRA code. The expected bunch parameters are reported in this paper. Further the discussion on advantages and drawbacks of the injector operation in low charge regime is given.

INTRODUCTION

After the installation of the third harmonic system at FLASH during the last shutdown it is possible to get bunches with well linearized distribution in the longitudinal phase space. This gives more opportunities for the bunch compression in the linac. So the development of 50fs FWHM sharp spike with high peak current is possible after the compression for the design bunch charge of 1nC [1]. The resulting bunch length at FLASH is no longer dominated by the nonlinearities in the longitudinal distribution but by the limits given by rf tolerances. Further reduction of the bunch length may be achievable either by operation with shorter laser pulses and larger transverse laser beam size or through the reduction of the bunch charge at the injection. While the first way requires significant effort for the laser readjustment and causes larger beam emittance the second one could be done with simple operational procedures. This would lead to smaller peak current though, but also to shorter bunch length and smaller emittance. For a variety of experiments it could be reasonable to operate with such a bunch even on cost of some SASE level.

Simulations with the ASTRA code have been done in order to find out the working points for the operation of the FLASH injector with the bunch charge in the range of 20-500pC and particularities which one may expect at such an operation. The results of these simulations will be discussed in this paper.

FLASH INJECTOR

The main components of the FLASH injector are:

- The laser system with an operation pulse length of 6.25ps while the pulse length of 4.4ps is possible. It can be operated with different laser spot sizes while the limit for the smallest size is uncertain. A good guess here could be 0.15mm rms transverse beam size. One can also go for smaller sizes. However the resulting electron beam distribution in the transverse plane will be no longer uniform.
- A 1.5cell cavity gun which is powered by the 5MW klystron. It is able to create the peak electric field of 45 MV/m which results in the bunch energy of 4.5-5-0MeV right after the gun..
- Next accelerating module consists of 8 nine-cell cavities (booster) with a gradient of max 40MV/m and is placed 3.047m after the cathode.
- For the emittance compensation a system of two solenoids, the main solenoid and the bucking coil is used. The main solenoid is shifted 27 cm downstream the cathode and operates usually in the range of 290-310A which corresponds to the max field strength of about 0,17T. The bucking coil is placed behind the cathode and is used to neutralize the residual magnetic field of the main solenoid. The detailed description of the FLASH injector can be found in [2].

OPTIMIZATION PROCEDURE

The optimization procedure which has been used for the simulations is based on the code written by M. Krasilnikov [3]. Originally it foresees two loops. In the main loop the parameters of the gun, both solenoids and laser are adjusted. Then for each choice of these parameters the second internal loop is carried out which looks for the best solution for the position, gradient and phase of the booster. The choice of the parameter to optimize is arbitrary. In this work the transverse emittance of the bunch at the end of the booster was optimized to its minimum for each working point.

Since the parameters of the inner loop are already fixed in the FLASH injector due to other operational reasons the initial optimization procedure in this work was reduced to the main loop only.

WORKING POINTS FOR LOW CHARGES

Since the main contribution for the emittance blow up is given by the space charge forces it is particularly important to accelerate the bunch to higher energies as fast as possible. As the matter of fact the gun gradient is always chosen near to the upper limit. However the energy of the bunch after the FLASH gun could be measured only indirectly over the probe signals. So one has to gather statistics over the probe signals at gun in order to determinate the peak gun gradient. The statistics about the readback values of these signals has been gathered over several months of the FLASH operation after the shutdown. Under the normal operation conditions the average readback value was found to be around 4.4MeV which corresponds to the peak electric field of 42.25MV/m. This value has been chosen then as a fixed parameter for the simulations.

The results for the calculated ideal working points for the on-crest operation with the bunch charges between 20 and 500 pC are shown in the table 1. The next table summarizes the values of the fixed parameters which have been assumed for the optimization procedure.

Table 1: Working points for FLASH injector operation with low bunch charge

Bunch Charge, pC	Laser Spot Size rms, mm	Max. Solenoid Field, T
20	0.085	0.1701
100	0.190	0.1710
250	0.275	0.1713
500	0.360	0.1715

One has to mention that the required laser spot size for the operation with 20pC is far beyond the lowermost limit which would assure a uniform transverse distribution of the electron bunch. Therefore it would be reasonable to go to larger spot size compared to the working point and thus to higher emittance in this case.

Table 2: Assumed fixed parameters in the simulation

Parameter	Value
Laser pulse length	6.25 ps
Gun gradient	42.25 MeV/m
Gun Phase	-0.9
Booster position	3.047 m
Booster gradient	34.00 MeV/m
Booster Phase	0.0

The main bunch parameters which one would expect if the injector is operated at its working points are summarized in the table 3 for bunch charges 20, 100, 250 and 500pC. These results can be compared with 2.5mm bunch length, 1,8mm mrad emittance and 40A peak current which are typical for the operation with the design bunch charge of 1nC. In general one may expect to get shorter bunches with tighter emittance on cost of the peak current. However the dependence of the bunch length on the bunch charge is not linear. For instance the reduction of the bunch charge from 1nC to 500pC leads to smaller emittance though, but doesn't change the bunch length significantly. To get stronger bunch contraction by change to lower bunch charges one has to reduce the laser pulse length. Currently FLASH injector is operated with the laser pulse length of 6.25ps which is somehow longer than the design value of 4.4ps. The simulations have shown already that the bunch length would reduce to 2.2mm and 1.8mm for 1nC and 500pC respectively in that case.

Table 3: expected bunch parameters at the end of the booster

Bunch Charge, pC	Normalised emittance, mm mrad	Slice emittance, mm mrad	Bunch length, mm rms	Peak cuurent, A
20	0.202	0.113	1.498	1.444
100	0.495	0.296	1.697	6.063
250	0.738	0.501	1.968	12.584
500	1.056	0.775	2.381	20.202
1000	1.832	1.355	2.5	41.7

SENSITIVITY OF THE WP FOR 500PC

The change of the bunch charge from 1nC to 500pC is the first step on the way to operation of the injector with low charges and is being established now at FLASH. In the following the sensitivity of the working point for 500pC with respect to solenoid and gun fields is discussed.

Sensitivity With Respect To the Solenoid Current

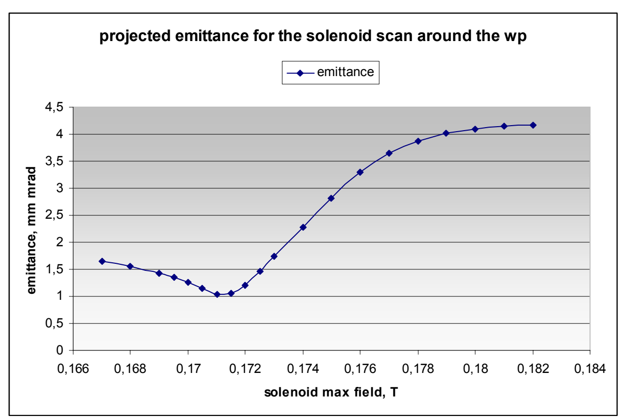

Figure 1: Projected emittance for the solenoid scan round the working point for 500 pC

Emittance compensation mechanism as it described for instance at [4] implements for each set of values for gun gradient and laser beam size an appropriate solenoid field in order to minimize the transverse beam emittance. The simulations have shown that the emittance doesn't go up at the same rate for the solenoid field above or below this optimal value (fig. 1). Also interesting is the behaviour of the beta function (fig. 2) at the end of the simulated path (end of the booster). It has only a local minimum at the optimal value of the solenoid field and its absolute minimum for a field strength which is about 4% higher.

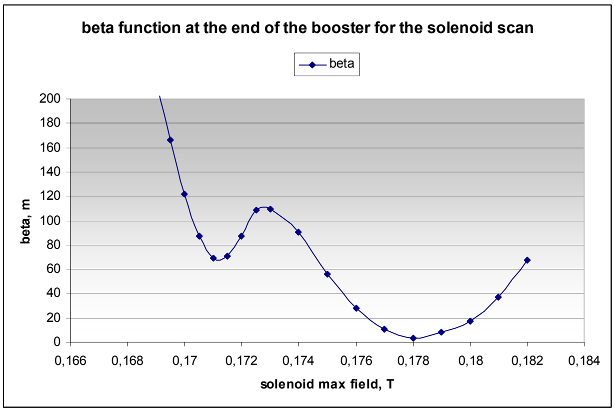

Figure 2: Beta function at the end of the booster for the solenoid scan at 500pC. The optimal value for the solenoid field with respect to the emittance was found to be 0.1715T. At this point the beta function has a local minimum though, but it achieves its absolute minimum for the field strength of 0.1718T.

This leads to the fact that the transverse beam size at the end of the booster becomes even smaller for higher solenoid currents in spite of higher emittance. Combined with more convenient twiss functions it becomes then easier to match the beam into the linac if the maximal solenoid field is slightly higher than at the calculated working point.

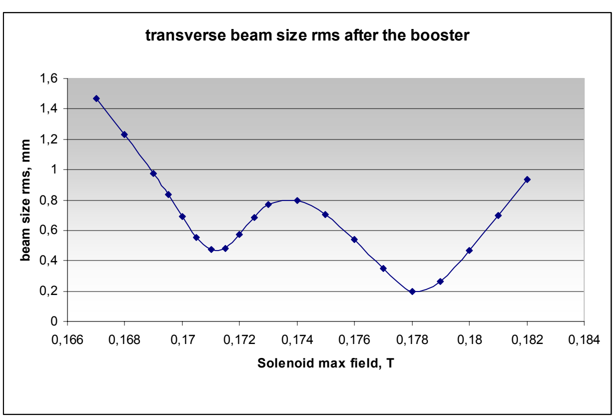

Figure 3: Transverse beam size rms at the end of the booster for the solenoid scan at 500pC

First attempts to operate FLASH with 500pC in June 2010 were also successful only with the solenoid current slightly above the best value. Hereby the emittance in the range between 3 and 4 mm mrad has been measured for the solenoid field of 0.178T which agrees well with the results of the simulations.

Table 4: sensitivity of the emittance and beta function with respect to the solenoid field strength

	+1%	-1%	+0.1 A	-0.1 A
Δε	73%	22%	2.48%	0.75%
Δβ	204%	---	3%	3%

The accuracy of the adjustment of the solenoid current at FLASH is given by 0.1A which corresponds to about 0.03% for the operation with 0.1715T solenoid field. The sensitivity scan has shown that this accuracy should be good enough to control the emittance and beta function within 3% (table 4)

Analogous scan for the gun gradient has shown that the claimed accuracy of the 0.01MeV would provide the control of the emittance up to 4% and of the beta function up to 20% (table 5).

Table 5: sensitivity of the emittance and beta function with respect to the peak electric field.

	+1%	-1%	+10 keV	-10 keV
Δε	29%	36%	4.2%	2.5%
Δβ	113.4%	48.5%	19.9%	3.9%

CONCLUSIONS

The working points for the operation of the FLASH injector with low charges have been calculated. It was found that the current diagnostics and laser system would allow its operation with bunch charge above 100pC. The sensitivity tests of the working point for 500pC with respect to the solenoid and gun fields have shown that the accuracy of these systems are good enough to control the emittance and optics fluctuations within reasonable corridor.

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